Detonation Science Blasts into a New Frontier

Livermore researchers (from left) Ralph Hodgin, Lisa Lauderbach, and Michael Bagge-Hansen prepare a high-explosive (HE) target at Livermore's High Explosives Applications Facility. (Photo by Randy Wong.)

HIGH-EXPLOSIVE (HE) detonation events unfold in a few millionths of a second. A high-voltage current vaporizes a thin metal foil within a specialized detonator, which throws a tiny plastic flyer—traveling around 2 kilometers per second—into an explosive. The impact shock initiates a detonation whose front propagates supersonically through the material as the explosive rapidly decomposes. After the energy release and associated chemical reactions conclude, many HEs leave behind excess carbon that condenses into solid soot.

At Lawrence Livermore, a key aspect of stockpile stewardship includes fine-tuning and experimentally observing HE detonation processes and developing computer models to predict the behavior of different HEs. Over the last several decades, HE detonation science has progressed toward higher resolution experimental and modeling capabilities that explore initiation processes, the precise chemical reactions involved and how quickly they occur, and the specific temperatures and pressures attained.

Accurate computer modeling of a detonation depends on understanding how quickly the carbon condensates, or allotropes (such as graphite and diamond), form within HE detonation soot. Previous research into this process has focused on validating microsecond phenomena. However, recent computer simulations have modeled the formation of carbon condensates at nanosecond timescales—an uncharted territory experimentally.

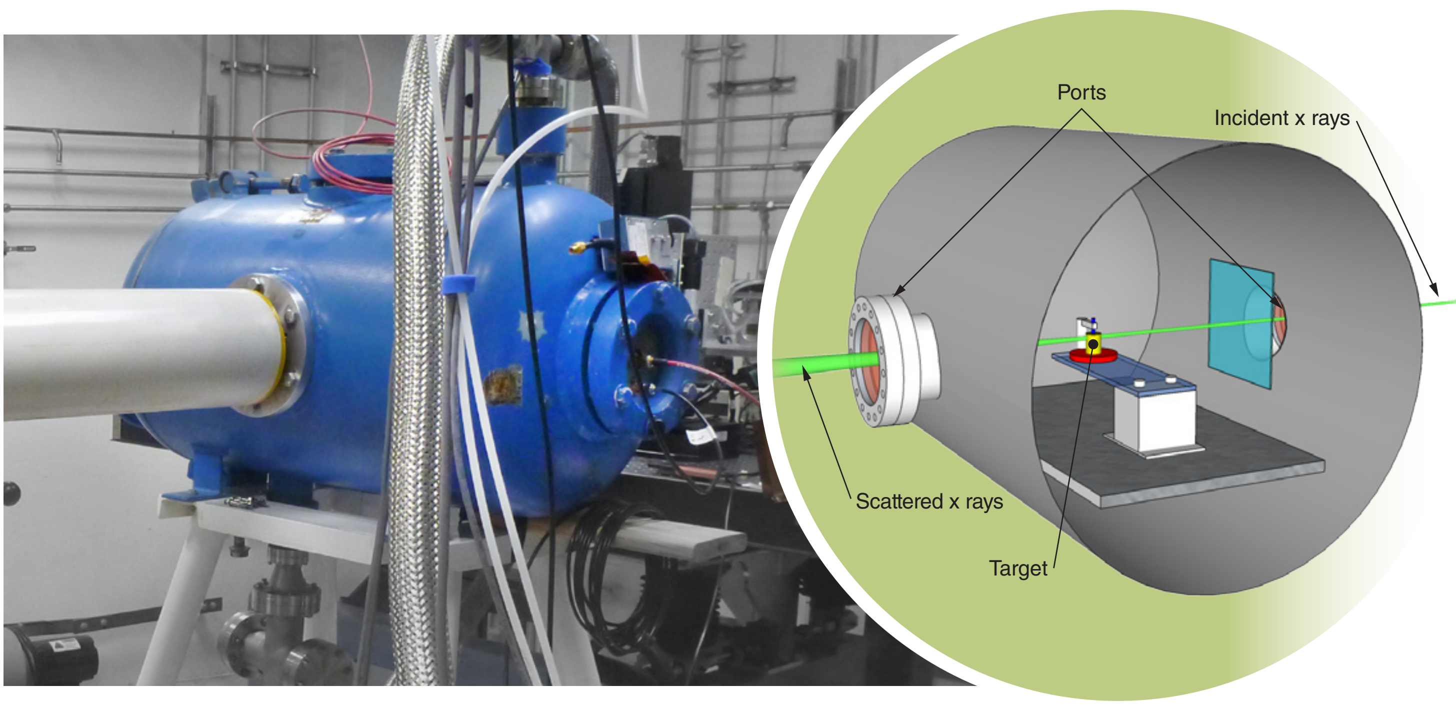
To validate the model predictions, a Livermore team led by physicist Trevor Willey has been investigating detonation processes using the intense, pulsed x rays at Argonne National Laboratory's Advanced Photon Source (APS) in Lemont, Illinois. "Detonation experiments produce so much visible light, and solid explosives are generally opaque. Therefore, determining what is happening—for example, optically—is difficult," explains Willey. "X rays help us penetrate deeply into the detonation with wavelengths conducive to observing nanoscale phenomena."

Livermore's multipronged approach marks the initial application of three-dimensional (3D) reconstruction algorithms to detonation systems involving an exploding foil initiator (EFI, or slapper). The effort also inaugurates the use of small-angle x-ray scattering (SAXS) for detonation experiments in the United States. Willey says, "For the first time, we can experimentally interrogate detonation phenomena on nanometer (billionths of a meter) and nanosecond (billionths of a second) scales." Initially funded by Livermore's Laboratory Directed Research and Development Program, the team's work has transitioned into small-scale detonation science experiments supporting various programmatic activities, including stockpile stewardship and defense nonproliferation.

Targets, a Tank, and Technology

Computer simulations of the performance of energetic materials rely on accurate input data related to the time-dependent shock initiation, the detonation process, its energy release, and formation kinetics of the resulting carbon condensate. The Livermore team designed small-scale detonation experiments to observe both detonator behavior and carbon condensate formation using a chemically diverse range of HEs. These experiments initially used cylindrical targets of HNS (hexanitrostilbene) and Composition B, which consists of RDX (trimethylenetrinitramine) and TNT (trinitrotoluene), fabricated at the Laboratory's High Explosives Applications Facility (HEAF). Target size varied by material, from a few hundred milligrams to a few grams, based on the minimum amount needed to maintain a self-propagating detonation.

To conduct repeated experiments, the team developed a mechanism for containing gas, soot, and other debris from the explosion. With the help of other HEAF colleagues, Lisa Lauderbach and Michael Bagge-Hansen outfitted a 120-liter steel



The custom-built detonation tank developed at Livermore provides a safe, reusable venue for conducting HE experiments. (inset) During a detonation, an ultrafast pulsed x-ray beam is fired onto the target at 153.4-nanosencond intervals. The scattering patterns for individual x-ray pulses are recorded and used to ascertain information about shapes and sizes of carbon condensates.

tank with a target platform, a vacuum-handling and exhaust system, and x-ray ports, while Ralph Hodgin, Chadd May, and others built the firing system. Meanwhile, the Dynamic Compression Sector (DCS), an intense x-ray beamline funded by the National Nuclear Security Administration and managed by Washington State University, was commissioned at APS. "The Dynamic Compression Sector provides an ideal place for dynamic shock and detonation experiments on fast timescales," says Willey, citing the facility's synchrotron radiation capabilities, which produce 50-picosecond x-ray pulses every 153.4 nanoseconds.

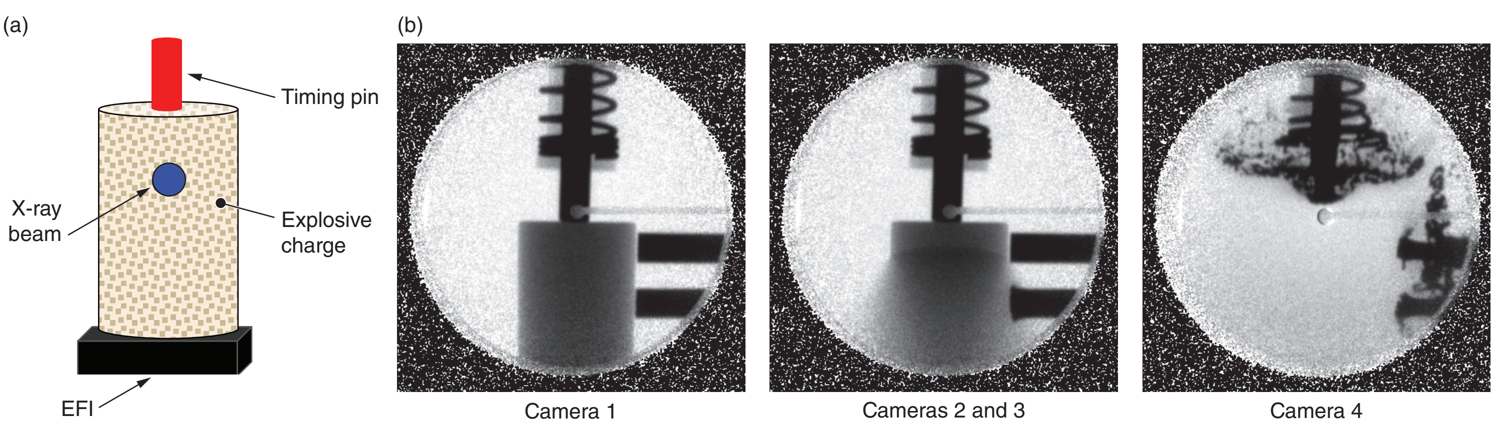
The researchers first conducted a series of EFI imaging experiments at APS. Subsequently, they installed their new tank at DCS, where they performed small-scale detonation experiments to better understand carbon condensate formation. The team collaborated with Los Alamos National Laboratory and National Security Technologies, LLC, who had been performing similar x-ray imaging tests. A four-camera array developed by Los Alamos was used to capture individual snapshots of x-ray pulses during the experiments.

Game-Changing Results

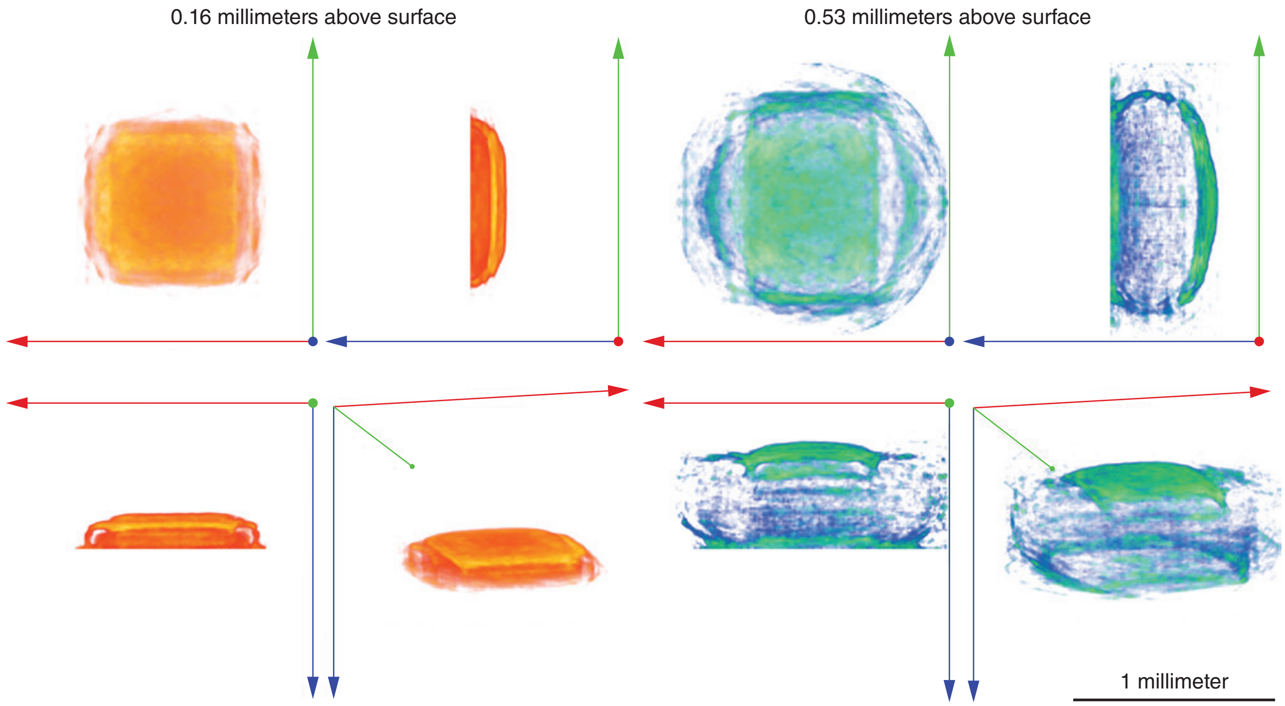
During the EFI experiments, APS's ultrafast pulsed x-ray beam provided high-resolution images measuring 1.5-by-1.5 millimeters at 153.4-nanosecond pulse intervals. EFIs were positioned at angles of 0, 15, 30, 45, 60, 75, and 90 degrees relative to the x-ray source and fired in these orientations. The resulting two-dimensional x-ray images, acquired at multiple angles, were input into a homegrown software package called Livermore Tomography Tools (LTT), which allows scientists to reconstruct 3D images of the EFI flyer at the pulse intervals. LTT's advanced iterative algorithms build 3D images of the object of interest from just a few views, in comparison to the typical thousands of views needed for computed tomography scans. As a result, the team captured the first detailed 3D images of flyers' kilometers-per-second motion during EFI operation.

Livermore's series of experiments on carbon condensates at DCS was no less compelling. Using the SAXS technique, the team resolved nanoscale details of the detonation. In this type of experiment, an intense but thin x-ray beam (approximately 50-by-100 micrometers) is fired directly through the sample. Scattering patterns for individual x-ray pulses were collected at 153.4-nanosecond intervals. Whereas previous studies showed condensate particle growth occurring over a few microseconds, the team's time-resolved SAXS imaging of HNS experiments demonstrated particulate growth within 400 nanoseconds after detonation. The Livermore team also observed that, once formed, graphite particulates generated from HNS detonations do not continue to change shape or size at microsecond timescales.

Determining particles' morphology and resolving their formation at faster timescales would not have been possible without the ability to perform SAXS on the four-camera array at DCS. In more recent experiments using other HEs, Willey and colleagues have observed nanostructures that range from complex and twisted to relatively flat. They have also noticed formation of nanodiamond particles and nanostructures with spherical shell graphitic layers resembling tiny "nano-onions." According to Willey, the team's data uncover possibilities for improving HE models and detonator performance. He says, "We're opening a new chapter in detonation science."



(a) An artist's rendering shows the setup for an experiment using an exploding foil initiator (EFI). A timing pin measures the time of the shock wave's arrival at the top of the charge. (b) A series of time-elapsed scatter-beam images, captured with the Dynamic Compression Sector's four-camera array, shows the upward progression of the detonation front.



The Livermore Tomography Tools software generates three-dimensional renderings of flyers in motion during EFI imaging experiments. Only seven views of the detonation were needed to create this reconstruction, which is viewed along x (red), y (green), and z (blue) axes.

Lighting the Fuse on New Experiments

Nanoscale characterization of HE processes has many applications. Commercially, nanodiamonds generated during HE detonations are used to seed synthetic diamond growth and are being explored for pharmaceutical purposes, fuel additives, and other uses. (See *S&TR*, March/April 2008, pp. 14–16.) In addition, the Laboratory's stockpile stewardship mission requires continual advancements to increase the safety, efficiency, and reliability of detonation technology. (See *S&TR*, July/August 2015, pp. 6–14.)

The team's tank setup has improved the fidelity and clarity of images showing flyers in motion during EFI detonation—data that will provide unprecedented feedback for new detonator designs. Future experiments will study changing detonation conditions to produce different pressure and temperature states for yielding supplementary postdetonation data on carbon condensates. Willey's team continues research with additional HEs, including DNTF (dinitrofurazanfuroxan), HMX (octogen), TATB (triaminotrinitrobenzene), and the Laboratory-developed molecule LLM-105.

Such breakthroughs in detonation experiments are inspiring new and early-career Laboratory scientists to pursue further advances in imaging and simulation capabilities. For example, researcher Will Shaw and colleagues are investigating another avenue related to EFIs by exploring in greater detail the initiation processes that occur when the flyer strikes the explosive. X-ray scattering expert Josh Hammons is coordinating construction of novel detector systems including camera configurations that capture two frames each to generate more images per detonation. Lawrence Fellow Mike Nielsen leads efforts to characterize the recovered detonation soot with transmission electron microscopy and related techniques. "Detonation is an interesting phenomenon," observes Willey. "With these technologies, we can conduct experiments that were not possible before."

—*Holly Auten*

Key Words: Advanced Photon Source (APS), carbon condensate, detonation science, detonator, Dynamic Compression Sector (DCS), exploding foil initiator (EFI), high explosive (HE), High Explosives Applications Facility (HEAF), Livermore Tomography Tools (LTT), small-angle x-ray scattering (SAXS).

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